

**Pulse-Power:  
A Possible Alternative to Chemicals  
for Zebra Mussel Control;  
Summary of 2000 Field Studies**

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**PURPOSE:** Field studies were conducted in 2000 to determine if the effects of pulse-power electric field systems could be evaluated by examining zebra mussel planktonic life stages. Evaluating plankton was a major variation from previous study methods and objectives. In the past, the older settlement stage was the target stage and a high control rate was the goal. In the 2000 studies, it was necessary only to have a consistent effect on plankton in the 20- to 60-percent range for them to be of value as a tool; high control of plankton was not expected or required. The first objective of the 2000 study was to evaluate effects of an electric field with a given set of electrical parameters on the behavior of planktonic zebra mussels. The second objective was to determine if the modified Megapulse electrical system would remain functional in a long-term settlement study.

**BACKGROUND:** Three species of macrofouling aquatic invasive species are well-established in North American water and have brought about well-documented habitat changes. These species will continue to have operational and financial impacts on industry and municipalities that use surface waters. Although there are suitable techniques for controlling these species, this Nation's shipping, agriculture, and municipal operations and infrastructure are still at risk from these and other species. Currently, there are only a limited number of chemicals and only a few nonchemical methods available to control biofouling in raw water supplies and associated structures such as pipes, pumps, and conduits (Figure 1).



Figure 1. Immature zebra mussels, such as the one pictured above, are being used in pulse-power testing

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**CHEMICAL CONTROL:** Chemicals are essential to produce much of what is needed in the modern world. Several types of chemicals control human pathogens in drinking water or growth of biofilm (slime) in industrial systems. Chemicals are most widely used to control macrofouling in industrial facilities, since they diffuse through the water and disburse rapidly. Given these attributes and sufficient residual concentration, chemicals can be used to treat industrial raw water systems from a facility intake to the point of discharge into receiving water (e.g., a lake, pond, or river). Chemicals kill organisms efficiently in facility conduits, are usually easy to apply and, depending on the type, can be applied reactively or proactively. Capital and application costs can be relatively low. However, total costs should include capital and application as well as requirements for operational and environmental permits.

In addition to costs, there can be other important considerations when using chemicals. In the last few decades, concerns have been raised over potential short- and long-term effects on materials in the facility, as well as on humans and on natural biota in receiving waters. These concerns persist regardless of the issuance of Federal and State use permits, application of required detoxification measures, and assurances of product safety from manufacturers.

Some chemicals can have operational and structural impacts such as corrosion or excessive sedimentation in conduits. Chemical handling and transport raise health and safety issues and environmental problems. Another concern is that chemicals, although easy to apply, can be difficult, if not impossible, to remove or completely deactivate when discharged. During discharges, a chemical residual in some form will typically be released, albeit at a low and permitted level.

Long-term accumulation and environmental fate of many chemicals are little understood and are becoming major concerns. Chemicals in the environment probably have the potential for widespread impact and could affect target and nontarget organisms, including humans. The fate of residual chemicals, either free in the water or bound to sediments, cannot be accurately predicted. Once a chemical is released, it can be years before it is identified as a problem, and then cleanup could be difficult and costly.

Often agencies and industries seek controls that will avoid some of the environmental issues associated with chemicals. The need to find alternatives could be accelerated, given that the USEPA and State agencies are in the process of adopting facility permit discharge limits using watershed-based water quality criteria. As a result, the use of many chemicals could become more restricted or eliminated. The need to find alternatives is becoming more important.

Unfortunately, alternative methods are usually subsystem-specific or structure-specific in mode of action and often do not perform as well as some chemicals. In addition, many proven approaches are reactive and not proactive. Rather than use a single chemical, a facility might have to use multiple non-chemical controls to achieve systemwide protection. Costs for multiple controls are site-specific, but could be very expensive.

**ELECTRICAL METHODS TO CONTROL ZEBRA MUSSELS:** Research on nonchemical controls has taken place in countries where macrofouling species cause problems. The objective has been to find controls that are effective and inexpensive and lack the environmental concerns of chemical methods. Information on these alternative methods can be found in scientific peer-reviewed publications, in literature that has not received peer review, or through vendor and

anecdotal sources. Prior to the invasion of zebra mussels (*Dreissena polymorpha*) into North America, forms of electrical technology were evaluated in Europe. In the last 10 years these electrical technologies have been evaluated in the United States and Canada. Several methods employ electrical energy to initiate a control such as ozone production or ultraviolet radiation. However, others rely either completely or partially on an electric field as the controlling factor. Three important controls include (1) plasma-spark/sonic systems, (2) cathodic protection systems, and (3) pulse-power electric field systems. All of these electric field technologies have been tested and in some cases applied to evaluate mussel control.

For electric field technologies, control energies are typically confined within or near facility conduits. Thus, unlike chemicals, these technologies do not affect the outside environment and have no residual effects. Relative to chemical releases, electrical technologies are environmentally benign and promise to be cost-effective. There are, however, wide variations in the manner in which electrical energy is employed in these methods. To avoid confusion regarding function of these electrical approaches, a brief summary follows (also see an overview by Smythe and Dardeau (1999)).

**Plasma-Spark/Sonic Systems.** These are also known as plasma-arc or spark systems (Mackie 2000) and can be legitimately considered pulse-power electrical devices, but should not be classed as providing control through generation of an electric field. An electrical discharge creates an in-water arc or spark. Most of this energy is then converted into other forms, including sound pressure waves. Although some of this electrical energy can actually kill zebra mussels, the sonic waves produced by the spark are the actual control mechanism (Smythe and Dardeau 1999; Smythe, Lange, and Tuttle 1997). Sparkers are designed to control settlement of adult mussels reactively, and possibly proactively, in straight sections of mid-diameter intake pipes (~0.6-1 m (~24-36 in)). Recent data indicate that intake pipes are protected for 50-100 m (several hundred feet) from the spark source (R. Schaefer, personal communication). It is unknown if the sound pressure waves will affect resident fish in source water at intake structures (G. Mackie, personal communication).

**Cathodic Protection Systems.** In this method, a low-voltage field is continuously generated (impressed) over the surfaces of a readily accessible structure, such as an intake trashrack or sheet-pile. It is assumed that the low voltage is an irritant to adult mussels but is not intended to be lethal for short-term exposure. Voltages are probably too low to affect the behavior or health of fish that reside in the vicinity of an intake. In full scale, a cathodic system was reported to reduce settlement on trashracks by about 75 percent (D. Comand, personal communication). Cathodic protection systems have been tested to control mussel settlement on specific structures (Smythe et al. 1991, Fears and Mackie 1995).

Neither the sparker nor the cathodic system will prevent downstream settlement of immature zebra mussels once past the controlling influence. The downstream area often includes small-diameter piping, pumps, fire protection sprinklers, and heat exchangers. A pulse-power electric field applied at the entrance to a service water system could be effective in simultaneously protecting all these components. Pulsed electric fields, cathodic protection, and spark systems used simultaneously could provide protection for all facility components.

**Pulse-Power Electric Field Systems.** Unlike spark and cathodic protection devices, these have the potential to proactively protect raw water from just beyond the intake through all of the service water system. It is likely that commercial versions will soon be available to protect small-diameter conduits and related components where there are few nonchemical options. In pulse-power devices, the electric energy field is confined between the electrodes. The induced field is several orders of magnitude more intense than the field produced by cathodic systems. Unlike the spark system, all water in the conduit passes between the electrodes; so all planktonic organisms are exposed to the electric field at some intensity.

The objective of the electric field technology is to kill or stun all the settlement-stage or younger mussels. This effect can be achieved only while organisms pass between the electrodes (a period of seconds to tenths of a second). The desired protection can be achieved even if mussels are not killed but are stunned and remain so until discharged from the facility, usually in 10 to 20 minutes. The electrodes are deployed inside a pipe downstream of the intake structure and trashracks. Upstream or downstream of the electrodes the field is imperceptible, and organisms in the source or receiving water are unaffected. The electric field causes no residual environmental effects.

It is likely that existing pulse-power electric fields could be scaled up to protect service water systems of 10,000 gpm ( $\sim 38 \text{ m}^3/\text{min}$ ) and at a cost less than or equal to that for some commonly used chemicals (K. Shoenbach, personal communication). It is also anticipated that electric field systems could be designed for use in large intake tunnels, although this has not been tested.

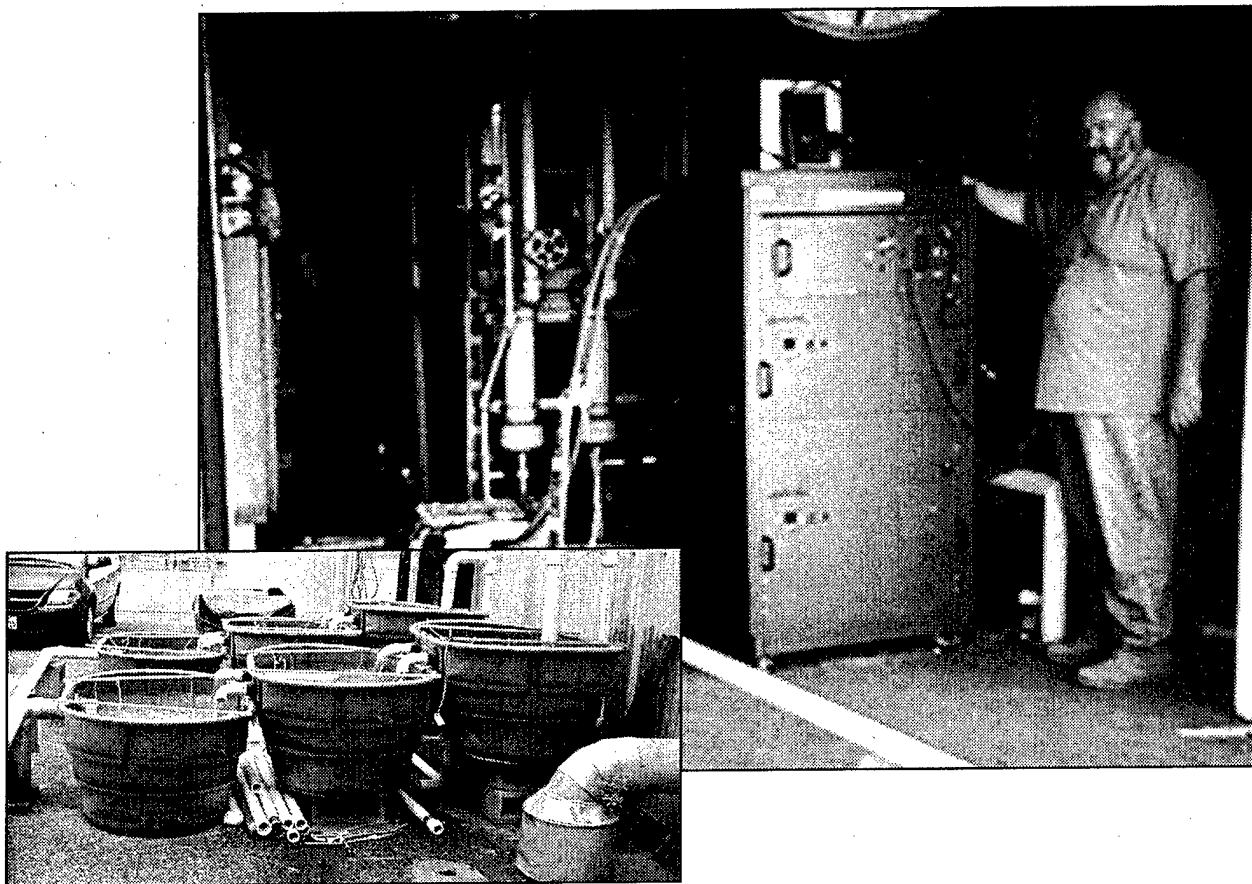


Figure 2. Pulse-power electric field system

**PAST PULSE-POWER ELECTRIC FIELD STUDIES:** Results of past pulse-power electric field studies, using equipment provided by Megapulse, Inc., that was a prototype of that used in the 2000 study reported in this technical note, indicated that mussel settlement downstream of the electrical test device was reduced at an efficiency of between ~40 and >90 percent (Smythe, et al. 1998; Smythe, Lange, and Schoenbach 1999). It was suspected that the wide variability in results was due primarily to equipment malfunctions, compounded by low seasonal mussel densities or facility conduit problems. Although the objective was to impact settlement-stage mussels, the effects of the field on the younger and smaller planktonic mussels were evaluated where possible. These microscope evaluations were to gauge functionality of the equipment and the potential success of the ensuing, relatively long-term settlement studies. Low planktonic mussel densities prior to settlement-stage tests hampered these evaluations.

Pulse-power studies were also conducted in the mid-1990s. Less sophisticated power supplies, outputting electric pulses at much lower energy levels than in the studies noted previously, were used. Electrode configurations were also dissimilar. However, even with the lower applied electrical energy the pulsed electric field controlled mussel settlement at rates of 78, 83, and 88 percent (Smythe et al. 1994, 1995). The results of all these studies, though promising, are confusing and indicate how little is known about the synergistic effects of electric field parameters and electrode configurations on aquatic organisms. Considering all the pulse-power data collected in the 1990s, it appeared that some adjustments to the electrical parameters and possibly the electrodes would result in a much more efficient system that could routinely control settlement at 80 to 90 percent. The problem was that it required essentially a year to evaluate system parameter settings and effects on settlement-stage mussels. A new approach or biological tool was needed to evaluate the effect in a matter of hours or even minutes. It was suspected that planktonic-stage mussels could be used as such a tool even though it was not necessary to control these younger and smaller life-stages to achieve control of the settling-stage mussel and related macrofouling.

To examine the potential of using planktonic life stages as the tool the U.S. Army Engineer Research and Development Center (ERDC), Entergy, the Tennessee Valley Authority (TVA), and Ontario Power Generation (OPG) co-funded a pulse-power electric field study in September 2000 to evaluate effects on plankton only.

**2000 ELECTRIC FIELD STUDY:** The 2000 study was designed to determine if short-term examination of zebra mussel planktonic life stages could be used to evaluate the effects of pulsed electric fields. Evaluation of the plankton was a major variation in study methods and objectives from all previous studies where the older settlement stage was the target life stage and a high control rate was the goal. Rather than expecting or requiring high control of plankton, it was necessary only to have consistent effect on plankton in the 20- to 60-percent range for them to be of value as a tool. The first objective was then to evaluate effects of an electric field with a given set of electrical parameters on the behavior of planktonic zebra mussels. The second objective was to determine if the modified Megapulse electrical system would remain functional in a long-term settlement study.

**Study Site and Methods.** This study was conducted at the Entergy Nine-Mile Point Fossil Plant in Westwego, LA, 10-17 September 2000 using a PVC test stand plumbed to a tap in the service water system. Raw Mississippi River water (~120 L/min) containing entrained plankton flowed into the test stand and was split into treatment and control portions.

The study used a Megapulse Loran C pulse-power generator, which was modified based on past studies (Smythe, Lange, and Shoenbach 1999). The generator output cables were attached to terminals on two 15- by 4-cm titanium electrode plates. One plate was located on each side of a clear Plexiglas electrode test cell, 4 cm square and approximately 1 m in length (the same apparatus used in previous studies). The cell was inserted into the treatment part of the stand. This cell was used since it worked previously and it was inexpensive. However, the electrode configuration caused the pulsed electric field to be generated approximately parallel to the flow of water, although perpendicular fields could be more effective. Voltage amplitudes were measured directly across the electrodes of the test cell. Pulse current amplitude was monitored using induction circuits and constantly displayed on an oscilloscope while the study was underway.

During tests the pulse rate was set to either 100 Hz (cycles/second), or 200 Hz on the Megapulse control panel. A pulse was a cycle of an electronically modified sine wave. The modification separated the positive and negative components (pulses) of the sine wave by 20 microseconds ( $\mu\text{sec}$ ) (Figure 3). This wave form was used exclusively in the 2000 study. The same wave was used initially in studies conducted in the late 1990s, although in these studies mussels were unintentionally exposed to variations of the wave form, such as half a sine wave (a unipolar pulse) output at 40 Hz (Smythe et al. 1998; Smythe, Lange, and Schoenbach 1999). It is unclear from existing data if biological effect is dependent on mussel exposure to a single cycle, multiple cycles of the bipolar sine wave, or its positive or negative component (/pulse). However, results suggest a unipolar pulse or series of pulses affect immature mussels and possibly settlement. Major operational cost savings are possible if a unipolar pulse is effective, assuming other factors are not altered. Given the potential cost savings and that the relationship (synergy) of wave form and polarity and mussel control mechanisms are not well understood, the electrical output of the Megapulse system is reported as pulses per second (pps) rather than Hz. A 100-Hz setting is thus reported as 200 pps and a 200-Hz setting as 400 pps to highlight the pulse component in the following descriptions and in Table 1. Each positive or negative pulse was 5  $\mu\text{sec}$  long.

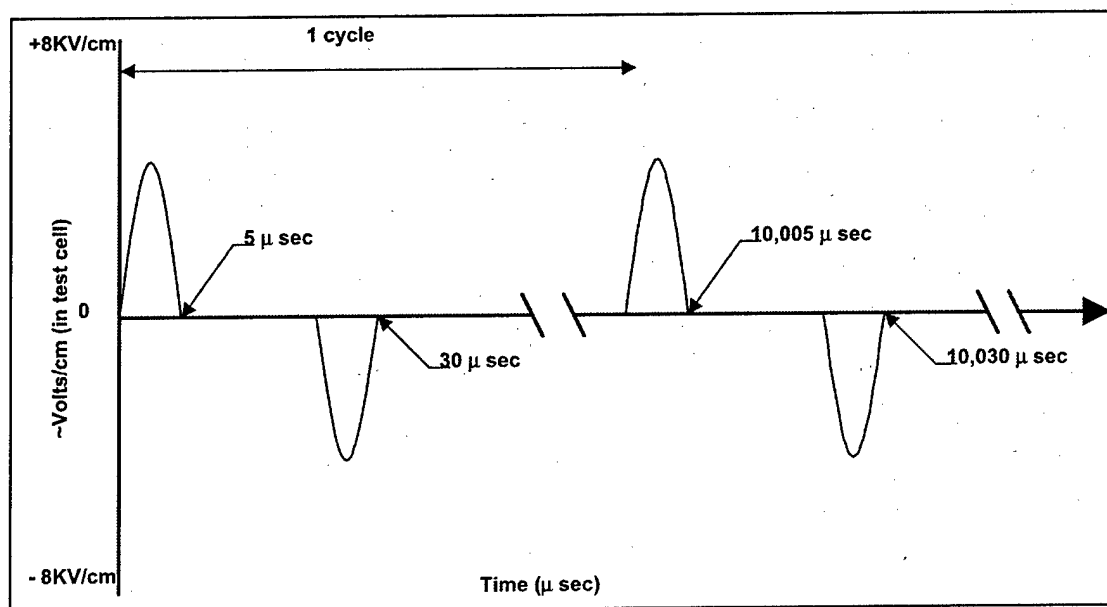


Figure 3. Pulsed wave form at 100 and 200 Hz (two cycles at 100 hz depicted) electric field study 2000

**Table 1**  
**Results of Pulse-Power Study, Conducted in September 2000, Westwego, LA**

Test <sup>1</sup>	Date	Pulse Rate (pps)	# Live	# Dead	Total #	% Dead	% Mortality Attributed to Treatment
C-1	9/12/00	-	32	8	40	20%	27%
T-1	9/12/00	200	20	18	38	47%	
C-2	9/12/00	-	32	8	40	20%	21%
T-2	9/12/00	200	16	11	27	41%	
C-3	9/12/00	-	64	16	80	20%	30%
T-3	9/12/00	400	16	16	32	50%	
C-4	9/12/00	-	28	9	37	24%	31%
T-4	9/12/00	400	19	24	43	56%	
C-5	9/13/00	-	72	9	81	11%	32%
T-5	9/13/00	400	24	18	42	43%	
C-6	9/13/00	-	70	8	78	10%	40%
T-6	9/13/00	400	20	20	40	50%	
C-7	9/13/00	-	65	10	75	13%	32%
T-7	9/13/00	400	38	31	69	45%	
C-8	9/13/00	-	80	14	94	15%	30%
T-8	9/13/00	400	53	43	96	45%	
C-9	9/14/00	-	36	8	44	18%	26%
T-9	9/14/00	400	35	28	63	44%	
C-10	9/14/00	-	49	5	54	9%	39%
T-10	9/14/00	400	32	30	62	48%	
C-11	9/14/00	-	39	7	46	15%	33%
T-11	9/14/00	200	29	27	56	48%	
C-12	9/15/00	-	51	8	59	14%	29%
T-12 <sup>2</sup>	9/15/00	400	28	21	49	43%	

Note: Numbers and percentages of live and dead organisms pertain to umbonal mussels.

<sup>1</sup> T=Treatment; C=Control

<sup>2</sup> Flow rate ~1/3 of all other samples

The electrodes were visually examined at the beginning and end of the study to determine if any salt (scale) or pitting was apparent. Electrode scale and pitting had been a problem in studies in the early 1990s (Smythe, Lange, and Schoenbach 1999).

The biological, in-field microscope evaluation of mortality and behavior of planktonic mussels in treatment and control samples followed the protocol used in ERDC studies conducted in St. Francisville, LA, in 1997 and 1998, and described in Smythe, Lange, and Schoenbach (1999). A 100-L tank was placed at the discharge of the control and treatment pipes and filled with water. A conical plankton net (0.5-m, 63 $\mu$  Nitex mesh) was partially immersed in each tank. Treatment and

control samples were collected simultaneously (i.e., in pairs), and the volume filtered by the nets was approximately equal for any given test run. Dissecting microscopes, fitted with cross-polarizing filters, were used to analyze the samples at 40x to 70x magnification. Samples were examined to characterize planktonic zebra mussel behavior and determine mortality. Samples were evaluated as quickly as possible after collection, typically within 10 min, and bottles were gently aerated during analyses. A mussel was assumed dead if there was no cilia or internal movement. Empty shells in both treatment and control were excluded from the evaluation. To determine if any long-term recovery (i.e., a stunned mussel classified as dead) or increased mortality was evident, one sample pair was re-examined later using the same methods.

**Results and Discussion.** The Megapulse system performed as prescribed with no electrical failures. There was no scaling or pitting on the electrodes. The average field strength, based on instantaneous voltage measured across the electrodes, was ~4.8 kV/cm and ~4.5 kV/cm, respectively, for the positive and negative pulses. Instantaneous current measurements ranged from slightly less than 100 to ~110 A, although fluctuations below 100 A were typical during tests, possibly due to changing water conductivity. With flow rates in the test stand of ~1 L/sec in each pipe, the velocity past the electrodes was about 66 cm/sec. At this flow it was estimated that mussels were exposed to less than ~45 effective pulses (or a little less than 23 sine-wave cycles) with the device set at 100 Hz, and ~90 or less at 200 Hz. The number of pulses applied to the flow in one sample pair was about 1.6 times more than other samples as flow in these samples was purposely slowed to 0.36 L/sec.

Density of zebra mussel larvae in raw water was approximately 2,000/m<sup>3</sup>, which was less than anticipated, but adequate for analytical purposes. The planktonic mussel population was almost entirely made up of umbonal stage rather than D-form<sup>1</sup> mussels. D-forms typically contribute to more than 80 percent of the population. Although the number of D-form mussels examined in the samples was documented, there were too few D-forms (typically less than 10 and often zero) to be used for analysis. The D-forms were not used when calculating mortality (Table 1). Settlement-stage mussels (plantigrade life stage), the largest dreissenid planktonic mussels, were not seen in the samples. This was anticipated since plantigrade mussels are typically the least abundant of planktonic dreissenids.

In this type of study, it is preferable to have mortality in the control sample at or below 10 percent. Mortality rates in control samples ranged from 9 to 24 percent, which is higher than preferred, but acceptable if it is assumed that the effect of treatment on plankton did not exceed approximately 50 percent.

Mortality rates were conservatively determined by simple subtraction of the percent mortality in a control sample from the mortality of mussels in its paired treatment sample. Mortality attributed to the electric field ranged from 21 to 40 percent. The mortality rate was not high when compared with the control, but a demonstration of effective planktonic control was not intended nor was it the objective of the study. Instead the objective was to demonstrate that individual test run mortality rates were of sufficient magnitude and consistent enough to instill confidence that the electric field configuration and electrical parameter settings (i.e., the synergy of factors) were affecting planktonic

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<sup>1</sup> So named because at this stage of development, the mussels resemble the capital letter "D" in shape.



mussels. The overall mean effect was ~31 percent mortality, and the range of effect among samples was relatively narrow, indicating that this study objective was achieved.

As mentioned, high mortality rate in planktonic mussels is neither expected nor necessary to achieve effective mussel control if effect on planktonic forms translates to greater mortality in larger settlement-stage mussels. It is the settlement stage that initiates fouling and is the target life stage for control using pulse-power electric fields. Results also indicate that planktonic mortality can potentially be used as a tool to indirectly gauge the effects of altering electrical parameters (e.g., pulse rate, amplitude, electrode array) to determine the synergistic effects on the more susceptible settling mussels.

The data revealed another possibly important finding related to future efforts and equipment designs. It was found that pulsing at 400 pps (or higher, probably) provided little or no more effect than pulsing at 200 pps. The mean induced mortality for three samples run at 200 pps was ~27 percent (with a maximum of 33 percent), whereas for the others run at 400 pps the mean was 32 percent (maximum 40 percent). Another sample was run at 400 pps, but at a reduced water flow, which effectively increased the pulse rate relative to all other samples. The mortality rate for this sample was less than the others conducted at 400 pps (29 percent), as well as the maximum for samples conducted at 200 pps. This suggests that mortality does not increase linearly as pulse rate increases.

The fact that a relatively consistent mortality was observed is encouraging, although it can be asked why the mean was only ~31 percent. The answer is probably related to mussel size and a lack of optimization in the electrode test-cell configuration. Electric field voltage potential is quantified using the term field strength, or volts per unit distance (e.g., v/cm in aquatic studies), which is the mean voltage over the specified distance. Relative to biology, there are thresholds of effect related to organism exposure to the synergy of an electric field's parameters. At low applied voltages, organisms typically do not detect, or at least do not respond to, an electric field. However, as voltage (field strength) increases (with other factors unchanged), thresholds of response are reached resulting in minor behavioral change, electronarcosis, or mortality, for example. Typically the response (or effect) increases directly with organism size and is commonly a function of the potential voltage difference, or the number of lines of force (lines of voltage equipotential) across a body. Therefore, if a sample of planktonic mussels is exposed to an electric field and some but not all die, the result suggests there were different-sized mussels in the sample. In any experiment, plankton size and life-stage variations occur within a sample (and among seasons) and results could be expected based on size alone. However, there is a confounding factor since field strength also varies within the test cell. Field strength is greatest at an electrode and decreases exponentially with distance such that a field is weakest in the central area between electrodes (for these studies this was in the central area paralleling a line between the 15-cm titanium plates). Thus, the field strength near an electrode was probably at a threshold to kill small and large mussels passing there, while the voltage was inadequate to affect smaller mussels passing through the central area of the cell. Given the applied voltage and the test cell used, mortality was a function of both mussel size and spatial distribution as they passed through the cell. A proposed change in electrode configuration would redistribute the field, eliminating the central area of relatively low field strength, and could contribute to a reduction in overall energy levels. Results of past experiments and the current study suggest that energy level can be reduced and relatively good results achieved where the larger target plankton are concerned. In these previous studies, the Megapulse system functioned at times at only

20 to 40 percent of the output in the 2000 study, whereas effectiveness on settlement fouling was still between ~42 and 92 percent. Results of past studies also suggest that with a modified test cell, levels of some other electric-field parameters can be reduced and effective control of fouling can still be achieved (~80 percent).

During this study and other ERDC-funded studies beginning in 1998, there was no obvious change in behavior for planktonic mussels not killed by the electric field. Additionally, there were no indications of increased mortality, recovery, or changes in behavior after more than 2 hr post-treatment, based on a limited time-series evaluation in 2000. This suggests the effect is an "all-or-nothing response," an effect that is not necessarily intuitive. However, the observed effect could be because of a mussel size threshold, as discussed previously, related to the level of synergistic effect of the applied electrical parameter settings, as well as a suspect electrode configuration.

The 2000 study, an ERDC-sponsored study in 2001 (only preliminary results determined), and previous electric field studies by ERDC and others (Smythe et al. 1991, 1994, 1995, 1998, Smythe, Lange, and Sawyko 1993; Smythe, Lange, and Schoenbach 1999) followed similar biological study plans, though equipment, electrical parameters, and electrode configurations varied. However, consideration of all data suggests the levels of some parameters used in 2000 could be lowered and synergistic impact on mussel settlement increased if parameter optimization is implemented. The levels could possibly be reduced by an order of magnitude.

**CONCLUSIONS:** Data indicate the modified electrical system will operate for an extended period and the fields generated can affect some portion of an entrained planktonic mussel population. The effect was relatively consistent and caused a maximum mortality of 40 percent, although surviving umbonal mussels exhibited no obvious behavioral effect. Study data could not be used to determine if the mortality was related to plankton size. However, study mortality rates based on the size theory fit the results of this and other studies. If the theory is correct, there is a high probability that plantigrade mussels under similar environmental conditions as in this study, exposed to optimized electric fields (i.e., synergy of parameter settings and electrode configuration are optimized), will be killed or stunned at overall energy levels below those tested in the 2000 study. This is an important point relative to fouling control. To be effective in most industrial or power plant situations, an electric field needs only to stun the settlement-stage mussels, although causing mortality would be an obvious advantage for control and in conducting studies. Based on the premise that the larger the organism, the greater the field effect, the older settlement-stage mussels should be more susceptible to a field than the D-form or umbonal forms. However, practical evaluation of the effects on settlement-stage mussels requires long-term settlement plate studies, proposed for future efforts where the improved Megapulse system can be used for extended periods. The 2000 data, combined with that from previous studies, indicate pulsed electric fields might be useful in proactive control of aquatic invasive or possibly native nuisance species.

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